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The Ohio State University
Research Foundation
Columbus, Ohio

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REPORT

by

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Investigation of . . . . Techniques for Measurement of Radar
Reflection Characteristics of Aircraft
and Missiles

Subject of Report . . . . The Echoing Area of Antennas

Submitted by . . . . Edward M. Kennaugh
Antenna Laboratory
Department of Electrical Engineering

Date . . . . 20 December 1957

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THE ECHOING AREA OF ANTENNAS

A. ABSTRACT

Various factors which affect the echo areas of parasitic antennas are discussed. The change in echo signal produced by load variations is derived. Several applications of parasitic antennas for echo modulation are suggested.

B. INTRODUCTION

The general requirements for a passive echo-enhancement device are: (1) it must intercept a large amount of energy from an incident radar wave, and (2) it must reradiate this energy directively toward the receiving antenna. It is clear that antennas are a class of devices which meet these requirements, although antennas as such are not commonly used for echo enhancement. The most familiar passive devices for echo enhancement are various forms of corner reflectors and more recently, the Luneberg lens with reflector. Both may be classified as optical devices whose principle of operation depends upon fairly obvious optical effects. In contrast, there is a wealth of existing information on various types of antennas to conform to almost any surface, and on the design of these to obtain radiation patterns of specified shape, but the application of these principles to echo enhancement has yet to be made.

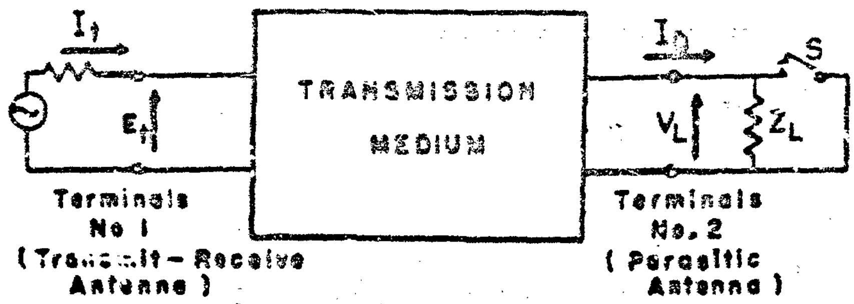
In contrast to normal antenna applications, to give a high radar return an antenna should be mismatched at the input terminals, with a non-absorbing load. Under these conditions, the energy extracted from the incident wave re-excites the antenna as a radiator, and a large back-scattered signal is obtained. We should expect the back-scattered signal to vary with the antenna orientation as the square of the radiation pattern, but this is true only if no other sources of back-scattered signal exist on the antenna structure. To separate the contribution due to the antenna mode, the load at the antenna terminals may be varied and the corresponding change in the back-scattered signal noted. This method has been suggested as a means of measuring aircraft antenna patterns by a model technique.[1,2]

The modulation of an echo signal by these means suggests several new applications of antennas as scatterers. The deleterious effects of amplitude and angular scintillation on high-resolution fire-control radar systems are well-known. These effects arise from fluctuations in amplitude and phase of signals reflected from various parts of a target. Fortunately, the spectral bandwidth of such fluctuations from most targets is limited, and these can be reduced by proper filtering. However, similar fluctuations may be induced by use of a pair of antennas mounted on the target. By modulation of the terminal impedance, amplitude and angular scintillation may be produced with any desired spectrum, with obvious electronic countermeasures applications. Another reason for imparting modulation to an echo signal is to identify targets by entirely passive means. In this connection, the antenna serves as a passive repeater, and a one-way secure transmission of information from target to radar is obtained with a minimum amount of equipment in the target.

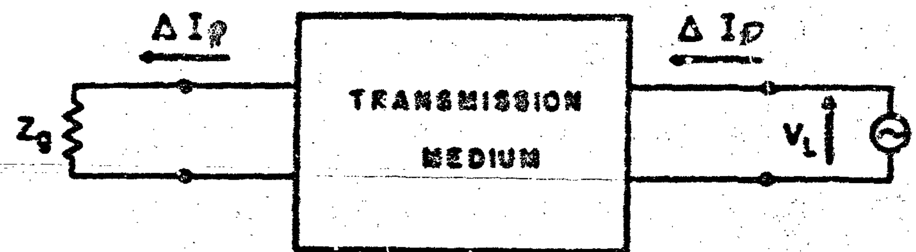
C. THE DETERMINATION OF ANTENNA ECHOING AREA

If an antenna is illuminated by a plane electromagnetic wave, there may be more than one source of scattering and diffraction. There may be (1) reflections from the supporting structure of the antenna, (2) reflections due to various antenna modes which are set up by the incident wave but are not normally excited from the antenna terminals, and (3) scattering due to excitation and reradiation of the normal antenna mode. For example, in scattering by a monopole above a ground plane, large reflections will occur from the ground plane itself, illustrating effect 1. In scattering by a sectoral horn, reflections will occur due to higher order modes set up in the horn which are not coupled to the antenna terminals, which illustrates effect 2. In each case, there will also be scattering due to the excitation of the basic antenna mode, providing the incident wave has the proper direction and frequency.

To identify the scattering due to the antenna mode, it is convenient to vary the antenna termination. The effect of this impedance change can be described by use of an equivalent generator at the antenna terminals, as stated by the Compensation Theorem. Referring to Fig. 1, the terminals of transmitting (and receiving) antenna and parasitic scattering antenna are indicated schematically as terminal pairs 1 and 2 of a 4-terminal network. The interposing medium, which is assumed linear and bilateral, can be replaced by the general network. If the transmitting antenna is energized with a generator as shown, and the impedance of the



(a) 4-terminal equivalent of antenna scattering.



(b) Equivalent generator replacing impedance variation.

Fig. 1. Equivalent circuits used to represent antenna backscattering.

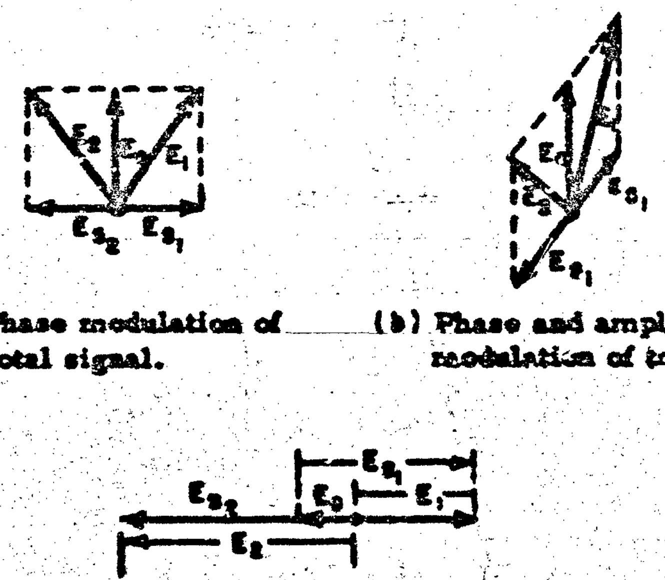
parasitic antenna termination is varied from Z_L to a short circuit by the closing of switch S, the change in voltage or current produced at terminal pair 1 is the same as that produced by a generator of terminal voltage V_L placed at terminal pair 2, all other generators being replaced by their internal impedances.

It is shown in the Appendix that the maximum change in received current ΔI_R is obtained when the load impedance Z_L varies from open circuit to short circuit and the parasitic antenna impedance is purely resistive. In this case the current variation is the same as that produced by a scatterer with echo area

(1) $$\sigma = \frac{G^2 \lambda^2}{\pi}$$

Where G is the power gain of the parasitic antenna over an isotropic radiator, in the given direction.

The echo signal amplitude E_1 (E_2) is the resultant of the varying component E_{s_1} (E_{s_2}) due to the load impedance change and a fixed component E_0 arising from scattering by the antenna support and higher order modes. Depending upon the relative phases of these signals, the echo signal amplitude may fluctuate as given in Eq. (1) or by smaller amounts. Figure 2 illustrates this effect for several different phases and amplitudes of the signal components.



(a) Phase modulation of total signal.

(b) Phase and amplitude modulation of total signal.

(c) Amplitude modulation of total signal.

Fig. 2. Effect of relative phase of signal components on total back scattered signal.

D. MULTIMODE ANTENNAS AS SCATTERERS

If a parasitic antenna is capable of supporting several different modes, each with its own characteristic radiation pattern, then the backscattering from such an antenna will be appreciable over antenna orientations where either mode may be induced. This effect may be

used to broaden the echo response of a parasitic antenna. We must distinguish between multimode operation and that of a single antenna mode, since a multimode antenna does not really have an unique pair of terminals, but rather as many terminal pairs as there are antenna modes. To illustrate this effect, consider the simple case of two identical antennas coupled to a single pair of terminals, as in Fig. 3.

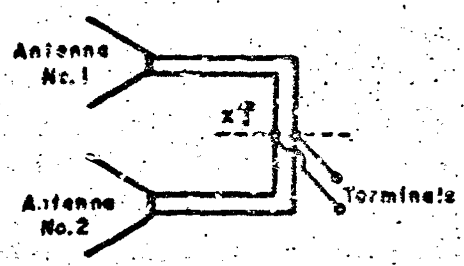


Fig. 3. Coupled antennas with variable terminal location.

Depending upon the position of the terminal pair along the coupling line in the x-direction, the relative phase of the excitation of each antenna will *vary* and by varying the location of the terminals, we can adjust the radiation pattern of the pair to be four times as strong as that of a single antenna in a given direction, although the position of the terminals must be altered whenever the direction of maximum reinforcement is changed. If we open-circuit the antenna terminals and illuminate the coupled antennas with a plane wave from the broadside direction, it is found that the backscattering will be four times that from a single antenna, since both antennas will reradiate in phase in this direction. It is assumed that all of the signal intercepted by one antenna is transferred without reflection or loss to the other, over the coupling line. Moreover, it is also readily seen that the backscattered signal is four times that for a single antenna for any direction of the incident wave, and for the same reasons. We can explain this by considering this antenna as a multimode structure, with virtual open-circuited terminals anywhere along the interconnecting line. The incident wave then excites one such mode and it is reflected at the corresponding open circuit termination to yield maximum backscattering in every case.

Extension of this principle to larger arrays has been suggested by Van Atta. Examples of a linear and circular array are shown in Fig. 4. These consist of arrays of N identical antennas coupled in pairs by transmission lines of equal length. The echo area of such an array is N^2 times that for a single antenna, and the backscattering pattern is just the square of the radiation pattern for a single member of the array. It is assumed that all reflections and loss in the coupling lines are eliminated, and that reflections from the supporting structures can be ignored.

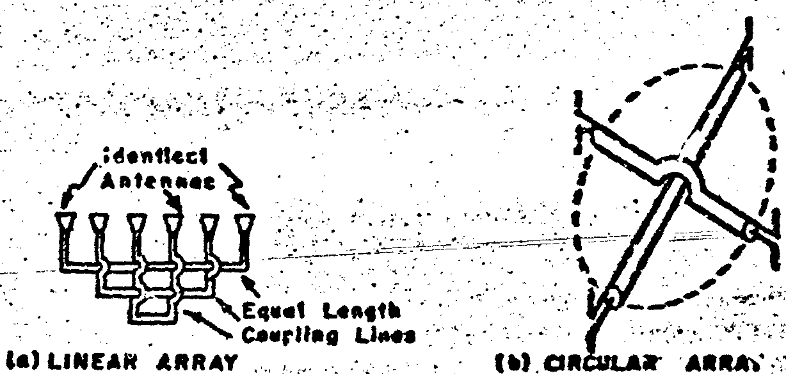


Fig. 4. Multimode antenna arrays for back scattering.

E. APPLICATIONS OF ECHO MODULATION BY ANTENNAS

1. Scintillation-Producing Devices for Electronic Countermeasures

The scintillation of a target adversely affects the performance of high-resolution fire control radars. This scintillation arises from interference between reflections distributed over the target surface. The spectrum of such fluctuations is limited by the target dynamics to relatively low frequencies, and this property may be used in enemy fire control radars to eliminate the more serious effects of scintillation by filtering. However, by mounting one or more parasitic antennas on the target and modulating the return from these at a very high rate, scintillation noise can be produced with any desired spectrum, and this should prove useful as a passive electronic countermeasure.

2. Target Identification Devices

A simple means of identifying various aircraft targets is needed, particularly for small private aircraft. By use of characteristic echo modulation frequencies, obtained with parasitic antennas mounted on the aircraft, a simple low-cost means of identification is possible. This will require a minimum of equipment in the aircraft, and permit identification at will by the ground radar.

3. Secure Communication Links

Since it is possible to transfer information via the modulation of a parasitic antenna with a minimum of equipment and weight, and over a directive beam between the interrogator and target with little chance of interception, this technique might be useful for transfer of information from a satellite vehicle. Interrogation could be made when the vehicle is near a ground radar station, and a minimum of equipment and space would be required in the satellite.

F. BIBLIOGRAPHY

[1]Sinclair, G., Jordon, E.C., Vaughan, E.W., "Measurement of Aircraft Antenna Patterns Using Models", Proc. IRE, Vol. 35, No. 12, December 1947, pp. 1451-1462.

[2]Gruber, J., "Investigation of the Method of Measuring Antenna Patterns by Utilizing the Reradiated Electromagnetic Field", M.Sc. Thesis, The Ohio State University, 1946.

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APPENDIX [redacted]

Assume a general disposition of transmit-receive antenna and parasitic scattering antenna. We shall assume that the polarization of transmit-receive antenna and the scattering antenna are identical, so that the transfer of energy between these may be described using scalar antenna heights . Now define

h_t Transmitting antenna height in direction of scatterer

h_p Parasitic antenna height in direction of transmitter

R Range of separation (assumed large)

λ Wavelength of radiation

Z_0 Free-space characteristic impedance

I_t Transmitting antenna current due to generator.

The far field intensity at the parasitic antenna produced by the transmitting antenna is, by definition of the antenna height,

$$(1) \qquad E^i = \frac{Z_0 I_t h_t e^{-jkR}}{2\lambda R} .$$

The induced open circuit voltage in the parasitic antenna is then

$$(2) \qquad V_{oc} = h_p E^i = \frac{Z_0 I_t h_t h_p e^{-jkR}}{2\lambda R} .$$

The voltage induced across a load Z_L at the parasitic antenna terminals is then

$$(3) \qquad V_L = \frac{V_{oc}}{(Z_p + Z_L)} Z_L = \frac{Z_0 Z_L}{(Z_p + Z_L)} \cdot \frac{I_t h_t h_p e^{-jkR}}{2\lambda R} ,$$

where Z_p is the input impedance of the parasitic antenna seen from its teriminals.

By the Compensation Theorem, the change in voltage or current produced by changing the load impedance of the parasitic antenna from

[redacted]

Z_L to 0 is the same as would be produced by a generator of terminal voltage V_L placed at the parasitic antenna terminals, all other generators being replaced by their internal impedances. Thus, the equivalent current in the parasitic antenna would be

$$\Delta I_p = \frac{V_L}{Z_p} \quad . \tag{4}$$

The incremental change in the field intensity at the transmit-receive antenna is

$$\Delta E^s = \frac{Z_0 \, \Delta I_p \, h_p \, e^{-jkR}}{2 \lambda R} \quad . \tag{5}$$

The corresponding incremental induced open-circuit voltage is

$$\Delta V_{oc}^R = \Delta E^s \, h_t = \frac{Z_0 \, \Delta I_p \, h_p \, h_t \, e^{-jkR}}{2 \lambda R} \tag{6}$$

and the incremental current flow in the transmit-receive antenna is

$$\Delta I_R = \frac{\Delta V_{oc}^R}{Z_t} = \frac{Z_0}{Z_t} \; \frac{\Delta I_p \, h_p \, h_t \, e^{-jkR}}{2 \lambda R} \quad . \tag{7}$$

Where Z_t is the sum of the transmit-receive antenna impedance and its load impedance as a receiver.

Combining Eqs. 1 through 7, the expression for the change in receiver current is

$$\frac{\Delta I_R}{I_t} = \frac{Z_0^2 \, Z_L}{Z_p Z_t (Z_p + Z_L)} \; \frac{h_p^2 \, h_t^2}{4 \lambda^2 R^2} \; e^{-2jkR} \quad . \tag{8}$$

The corresponding increment in receiver current caused by the addition of a scatterer at the range R, with echo area σ, is

$$I_R = \frac{E^s \cdot h_t}{Z_t} \tag{9}$$

where

$$(10) \qquad E_s = \frac{\sqrt{\sigma}}{\sqrt{4\pi R^2}} E^i$$

and E^i is given by Eq. 1. Combining, we have

$$(11) \qquad \frac{I_R}{I_t} = \frac{Z_o}{Z_t}\sqrt{\sigma} \frac{h_t^2}{4\lambda\sqrt{\pi R^2}} e^{-2jkR} \quad .$$

For equality of the signal from the scatterer and antenna, we must have

$$(12) \qquad \sqrt{\sigma_{eq}} = \frac{Z_o Z_L}{Z_p(Z_p + Z_L)} \frac{\sqrt{\pi}}{\lambda} h_p^2 \quad .$$

To relate σ_{eq} to the antenna gain, we must relate this quantity to the antenna height. From Eq. 1, the ratio of input power to an antenna to the far field power density can be computed and compared with that for an isotropic antenna to find the gain G:

$$G = \frac{\text{power density in given direction}}{\text{power density of isotropic antenna with same input power}}$$

$$(13) \qquad G = \frac{\left(\frac{E^2}{Z_o}\right)}{\left(I^2 \frac{R_e(Z)}{4\pi R^2}\right)} = \frac{Z_o}{R_e(Z_p)} \frac{\pi}{\lambda^2} h_p^2 \quad ,$$

so that Eq. 12 becomes

$$(14) \qquad \sqrt{\sigma_{eq}} = \frac{Z_L R_e(Z_p)}{Z_p(Z_p + Z_L)} \frac{\lambda}{\sqrt{\pi}} G \quad .$$

[redacted]

The equivalent echo area is

$$\text{(15)} \qquad \sigma_e = \left[\frac{Z_L \, R_e(Z_p)}{Z_p \, (Z_p + Z_L)} \right]^2 \frac{G^2 \lambda^2}{\pi} \quad .$$

We can simplify the expression involving the impedances since

$$\text{(16)} \qquad \frac{Z_L \, R_e(Z_p)}{Z_p(Z_p + Z_L)} = \frac{R_e(Z_p)}{2Z_p} \left[1 + \left(\frac{Z_L - Z_p}{Z_L + Z_p} \right) \right] = \frac{R_e(Z_p)}{2 \, Z_p} \left[1 + \Gamma \right]$$

where Γ is the voltage reflection coefficient of the load impedance Z_L. This implies

$$\text{(17)} \qquad \sigma_{eq} = (\text{P.F.})^2 \, |1 + \Gamma|^2 \, \frac{G^2 \lambda^2}{4\pi}$$

where P.F. denotes the power factor of the parasitic antenna impedance. The maximum change in signal is obtained when the power factor of the parasitic antenna impedance is unity, and when the antenna terminals are alternately open and short-circuited. In this case, the equivalent echo area is

$$\text{(18)} \qquad \sigma_{eq} = \frac{G^2 \lambda^2}{\pi} \quad .$$

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